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SUMMARY

Powder-metallurgy tungsten both with and without 1/4-inch-thick molybdenum cladding was reduced 12:1 by extrusion in the temperature range 2400° to 4000° F. With cladding, extrusion was possible with preheat temperatures as low as 2400° F. Unclad billets could not be extruded with preheat temperatures less than 2800° F. Extrusion temperature and technique (clad or unclad) affected the as-extruded hardness, grain size, and room-temperature tensile strength. Tensile strengths at 3000° and 3500° F were not influenced by extrusion temperature or technique. There was no correlation between the elevated-temperature ductility and the post-test hardness or grain size.

INTRODUCTION

Because of low ductility, tungsten is difficult to fabricate by conventional metal-working processes. Tungsten has been extruded, but extrusion has been primarily employed as a breakdown operation to refine grain structure and to yield materials suitable for such further working procedures as forging, swaging, or rolling. For the most part, this preliminary breakdown extrusion has been limited to reductions of 3:1 to 8:1. Increased interest in the use of alloyed or dispersion-strengthened tungsten for aerospace applications has generated a need for greater extrusion reduction ratios. In the aforementioned instances, a wrought structure may be desirable for high-strength properties. Wrought structures have been achieved with many dispersion-strengthened materials, even when extruded at temperatures approaching 0.8 of their melting points. However, in the case of tungsten, for example, the use of relatively high homologous temperatures for extrusion increases the likelihood of undesirable metallurgical reactions between the matrix and refractory particle additives and may pose problems of a practical nature, such as furnace-temperature control, die erosion, container abrasion, etc.

The utilization of cladding to promote the extrudability of difficult-to-extrude materials at moderate temperatures has been reported by numerous investigators (refs. 1 to 8). Tungsten and tungsten-base alloys or composites have been successfully extruded with the use of various thicknesses of cladding and a variety of cladding materials ranging from mild steel to high-strength molybdenum alloys (refs. 1 and 4 to 9). The major benefits that apparently have been derived from the use of cladding have been protection of atmosphere-sensitive materials during preheating and extrusion, improved lubrication during extrusion, decreased temperature loss in the billet material during transfer from furnace to extrusion press, and a possible isostatic force field about the billet which may have aided plastic flow of the billet. All these factors have led to a greater yield of useful material and have provided specific advantages.

Despite wide use of cladding in the extrusion of tungsten materials, most studies conducted to date contained no direct comparison of the properties of the tungsten extruded with and without cladding. This investigation, therefore, determined the influence of cladding on both the extrudability and the properties (particularly strength) of tungsten extruded over a wide range of temperatures. It was anticipated that the results obtained could be utilized as background information for the production of tungsten-base alloys or dispersion-strengthened materials.

A total of 14 billets were produced from nominal 4.5-micron commercial tungsten powder by utilizing conventional powder-metallurgy processes. Billets with molybdenum cladding (nominally 1/4 inch thick) were extruded with preheat temperatures of 2400° to 3800° F. Billets without cladding were extruded with preheat temperatures of 2800° to 4000° F, and extrusion attempts were made at temperatures as low as 2600° F. In all cases 12:1 reduction dies were used. Tensile tests of as-extruded material were conducted at room temperature, and at 3000° and 3500° F. Chemical analysis and metallographic studies were carried out, and hardness, grain size, and density were determined.

MATERIALS, APPARATUS, AND PROCEDURE

Preparation of Specimens

Raw materials. - The tungsten utilized in the preparation of the billets studied in this investigation was a commercial grade supplied by the General Electric Company. The nominal particle size of the powder was 4.5 microns. The chemical analyses of the as-received powder and of the extruded billets are shown in table I.

Cleaning. - In order to minimize impurities and to improve compactability, the powder was precleaned in a flowing atmosphere of purified dry hydrogen prior to press-

TABLE I. - CHEMICAL ANALYSIS OF TUNGSTEN MATERIALS

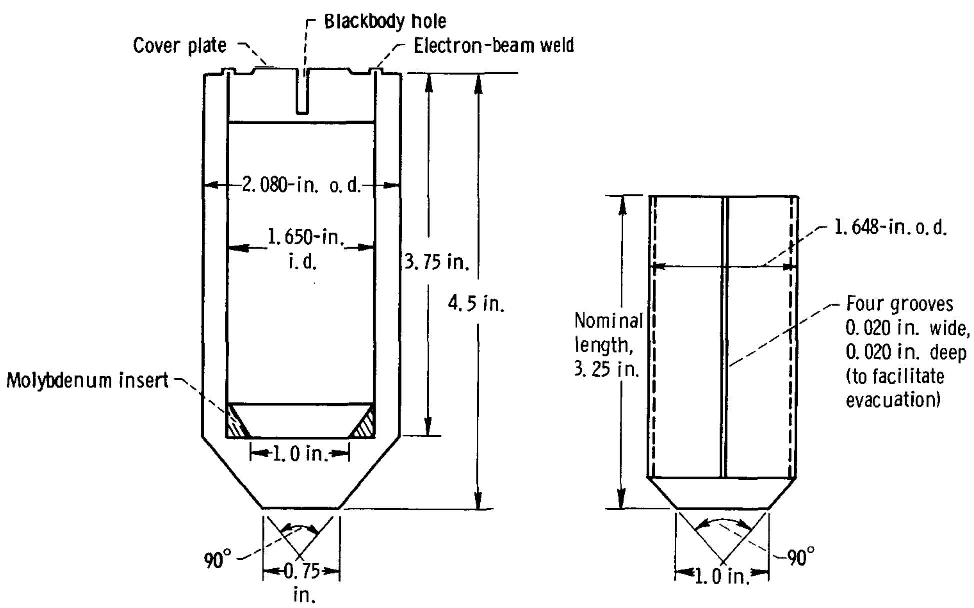
[Carbon content determined by combustion with chromatographic technique; oxygen content determined by inert gas fusion; all other elements determined by semiquantitative spectrographic analysis.]

Element	Concentration, ppm	
	Supplier's analysis of as-received powder	Typical extruded specimen
Carbon	10	4
Oxygen	1200	10
Magnesium	10	Not detected
Silicon	10	Not detected
Iron	10	10
Molybdenum	Not detected	10

ing. The cleaning procedure employed has been described in reference 8.

Pressing and sintering. - The cleaned tungsten powder was hydrostatically compacted at room temperature and at a pressure of 30 000 pounds per square inch. The compacted billets were then given a duplex sintering treatment that consisted of 2 hours in dry hydrogen at 2600° F followed by 4 hours in vacuum (5×10^{-5} torr) at 4000° F. The as-sintered density of the tungsten billets, determined by water immersion, was approximately 85 percent of theoretical density.

Canning. - Seven of the sintered billets were canned in nominally 1/4-inch-thick pressed and sintered molybdenum cans, the density of which was 95 percent of theoretical. The shapes and dimensions of the extrusion billets and cans are shown in figure 1. The remaining seven billets were not canned. The uncanned billets were machined to the same outside dimensions as the molybdenum extrusion cans. All machining of both the billets and the cans was done dry. To remove volatile contamina-



(a) Molybdenum extrusion can.

(b) Tungsten extrusion billet.

Figure 1. - Extrusion billet and can.

tion which may have been picked up during machining and handling, each can and billet assembly was fitted together, a lid was inserted, and the entire assembly was heated at 4000° F for 2 hours in a vacuum of 5×10^{-5} torr. The uncanned billets were given a similar heat treatment prior to extrusion. The cleaned billet-can assemblies subsequently were sealed by electron-beam welding.

Extrusion. - A vertical three-stage 1020-ton Loewy hydropress (ref. 10) equipped with nominal 2-inch-diameter tooling and preset to produce a maximum stem stress of 200 000 pounds per square inch was used for the extrusion operations. Billets were inductively preheated in flowing hydrogen (5-8 SCFH) to measured temperatures of 2400° to 4000° F, transferred to the press, and extruded through zirconium-oxide-coated, 90° tool-steel dies. The total time from removal of the billet from the preheat furnace to completion of the extrusion was 3 to 8 seconds. The nominal preheat temperatures were adjusted to account for temperature losses that may have been incurred during transfer of the billets from the preheat furnace to the extrusion press. In a prior calibration, a determination had been made of the temperature drop sustained by a dummy 2-inch-diameter billet after various times following pullout from the preheat furnace (at 4000° F). Since, presumably, the billets were in air during the major portion of the time, the nominal preheat temperatures were adjusted to give a better indication of the actual temperature of the billets at the times of entry into the extrusion container. Table II, p. 6, shows actual preheat temperatures and adjusted extrusion temperatures. All billets (clad and unclad) were extruded through 12:1 reduction ratio dies. Under these conditions, maximum measured extrusion stem stresses were 123 700 to 200 000 pounds per square inch with measured ram speeds of 0.4 to 5.0 inches per second. The techniques for determining stem stresses and ram speeds are described in reference 10. The ram travel was adjusted so that a maximum butt length of 1/16 inch would remain in the container if the material were fully extruded. Increasing butt lengths beyond about 1/16 inch would be indicative of a general decrease in extrudability.

Examination and Evaluation

Extruded bars were examined visually and radiographically for flaws. Specimen blanks were then cut from the bars for subsequent determination of tensile properties at room temperature and at elevated temperature. Test pieces were taken from the nose, middle, and tail of each rod for metallographic examination, chemical analysis, and determination of reduction ratio, density, room-temperature hardness, and grain size. With the unclad billets a die wash of 0.018 to 0.040 inch resulted in a slight variation in reduction ratio from nose to tail; therefore, average values were determined. There was no significant variation in other measured properties from nose to tail of any of the extrusions (clad or unclad); therefore, results from the middle of each bar are reported.

Reduction ratio. - The reduction ratio obtained for each extruded billet was determined by measuring the initial and final diameters. In the case of the clad extrusions, the thickness of the cladding was subtracted to give the final core diameter.

Density. - Density determinations of the extruded materials were made by using mercury displacement of machined specimens. The reported values are the averages of two determinations and are believed to be accurate to ±0.02 gram per cubic centimeter.

Hardness. - Hardness was determined by means of a 136° diamond-pyramid indenter with a 1-kilogram load. The average of five hardness determinations taken near the center of a longitudinal section was used for the as-extruded billets. The average of three hardness determinations taken on a longitudinal section about 1/16 inch from the fracture edge was used for the measurements carried out after tensile testing.

Grain size. - Grain size was determined for each extruded billet and for each tested specimen on longitudinal sections by using the Heyn intercept method (ASTM specification E112).

Tensile testing. - Specimens for room-temperature and elevated-temperature testing were machined from the as-extruded billets. The tensile specimen design is shown in figure 2.

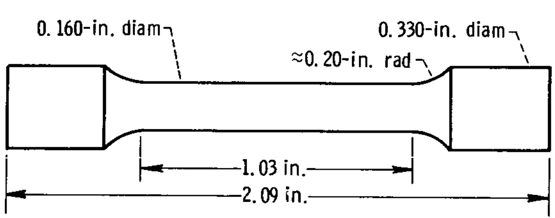


Figure 2. - Tensile specimen.

Tensile tests were conducted with screw-driven Instron tensile machines. For the elevated-temperature tests, a tensile machine was equipped with a water-cooled vacuum chamber (1×10^{-5} torr) and a tantalum sleeve heater. Specimen temperature was measured with a tungsten - tungsten-26-percent-rhenium thermocouple located at the midlength of the specimen. The measured temperature was estimated to be accurate to ±25° F. Crosshead speed was 0.02 inch per minute. A strip-chart recording of load against crosshead displacement was obtained for each test. Reduction in area was determined just below the fracture edges of the specimens.

RESULTS AND DISCUSSION

Extrusion results for the 14 powder-metallurgy tungsten billets studied are presented in table II; included also are percent of theoretical density, hardness, grain size, and microstructure obtained for each of the extruded billets. The densities of all extruded materials were in excess of 99 percent of theoretical (99.3 to 99.8 percent) and appear completely independent of extrusion temperature or technique (i.e., with or

TABLE II. - EXTRUSION RESULTS

Billet	Extrusion preheat temperature, °F	Billet transfer time, sec (a)	Adjusted extrusion temperature, °F (b)	Maximum measured extrusion pressure, psi	Ram speed, in./sec	Reduction ratio based on initial and final dimensions of tungsten billet	Extruded length, in.	Butt length in container, in.	Percent of theoretical density	Diamond pyramid hardness with 1-kg load	Grain size, ASTM number (c)	Lubrication practice		
												Container	Die	Follower block
Molybdenum-clad billets														
1	3800	7	3640	123.7×10^3	3.2	10.6:1	$38\frac{1}{2}$	0	99.7	364	8.4	Copper plus glass cloth	Zirconium dioxide	Glass
2	3400	4	3310	189.6	2.8	10.1:1	$38\frac{1}{2}$	0	99.4	368	8.5	Tungsten disulfide plus glass cloth	Zirconium dioxide plus tungsten disulfide	Graphite
3	3000	5	2930	200.0	3.1	10.9:1	35	$\frac{1}{16}$	99.4	379	8.5			
4	2800	6	2730	200.0	5.0	10.7:1	30	$\frac{1}{4}$	99.8	367	9.0			
5	2600	7	2530	200.0	4.6	10.9:1	$29\frac{1}{2}$	$\frac{5}{16}$	99.6	386	10.25			
6	2500	8	2420	200.0	4.0	10.4:1	$25\frac{1}{2}$	$1\frac{1}{16}$	99.6	432	12.0			
7	2400	4	2370	200.0	4.4	10.9:1	$29\frac{7}{8}$	$\frac{3}{4}$	99.6	435	12.75			
Unclad billets														
8	4000	4	3880	155.6×10^3	2.0	10.4:1	$30\frac{1}{2}$	(d)	99.7	387	8.25	Tungsten disulfide plus glass cloth	Zirconium dioxide plus tungsten disulfide	Graphite
9	3500	8	3330	200.0	0.8	10.6:1	$26\frac{3}{4}$	$\frac{3}{8}$	99.6	383	8.25			
10	3000	3	2960	200.0	1.6	10.9:1	$23\frac{3}{4}$	$\frac{3}{4}$	99.7	388	8.8			
11	2800	5	2750	200.0	0.4	10.4:1	$23\frac{3}{4}$	$\frac{9}{16}$	99.7	381	9.0			
[e]12	2600	4	2560	200.0	---	------	---	---	----	---	----			
[e]13	2600	4	2560	200.0	---	------	---	---	----	---	----			
[e]14	2600	(f)	----	-----	---	------	---	---	----	---	----			

[a]Total time from removal from furnace to completion of extrusion.
[b]Based on temperature drop in dummy billet.
[c]All specimens exhibited equiaxed structure.
[d]Butt length not recorded.
[e]Sticker, no extrusion
[f]No transfer time recorded.

TABLE III. - PROPERTIES OF EXTRUDED AND TESTED MATERIALS

Billet	Adjusted extrusion temperature, °F	Test temperature, °F	Ultimate tensile strength, psi	Percent reduction in area (a)	Diamond pyramid hardness with 1-kg load	Grain size, ASTM number (b)
Molybdenum-clad billets						
1	3640	Room	22.1×10^{3}	[c]0	353	7.5
		3000	14.0	45	330	7.5
		3500	9.5	36	316	7.0
2	3310	Room	30.8×10^{3}	0	375	8
		3000	12.2	15	364	7.5
		3500	8.5	25	346	5.5
3	2930	Room	40.6×10^{3}	0	365	7.2
		3000	12.6	12	316	8.5
		3500	7.8	19	284	7.5
4	2730	3000	8.5×10^{3}	4	310	7.75
			12.1	26	317	8.5
5	2530	Room	86.2×10^{3}	[c]0	392	9.75
		3000	12.7	17	300	8.25
		3500	9.4	25	284	7.5
6	2420	Room	93.1×10^{3}	0	423	12
			113.2	0	421	12.25
		3000	12.5	16	300	8.25
		3500	8.3	22	301	9.5
			7.9	19	263	9.0
7	2370	Room	88.2×10^{3}	0	441	13.0
		3000	13.8	31	348	7.75
			12.1	37	332	7
		3500	7.8	25	315	7
			8.2	34	324	9

Billet	Adjusted extrusion temperature, °F	Test temperature, °F	Ultimate tensile strength, psi	Percent reduction in area (a)	Diamond pyramid hardness with 1-kg load	Grain size, ASTM number (b)
Unclad billets						
8	3880	Room	42.3×10^{3}	0	368	7.25
			38.3	0	368	6.75
		3000	12.3	16	365	6.25
		3500	8.2	26	354	5.75
9	3330	Room	45.5×10^{3}	0	373	8
			45.0	0	---	----
		3000	12.3	18	337	6.75
		3500	8.4	24	319	5.75
			8.2	26	351	6.0
10	2960	Room	92.3×10^{3}	0	386	9.0
		3000	13.8	23	299	9.0
		3500	8.8	23	261	9.5
11	2750	Room	117.2×10^{3}	0	379	9.5
		3000	13.5	27	291	9.5
		3500	8.8	22	265	9.25
[d]12	2560	-----	---------	--	---	----
[d]13	2560	-----	---------	--	---	----
[d]14	[e]2600	-----	---------	--	---	----

[a] All specimens failed by brittle fracture except that from billet 1 tested at 3000° F, which was ductile.
[b] All specimens exhibited equiaxed structure.
[c] Failed at radius.
[d] No specimens.
[e] Preheat temperature; no transfer time recorded.

without the use of cladding). Hardness and grain-size data for the as-extruded materials are presented in subsequent figures for comparison with values obtained on the tested tensile specimens. The as-extruded microstructures are described in the section Metallographic Examination.

The results shown in table II make it immediately apparent that clad billets were successfully extruded at preheat temperatures as much as 400° F below that of the unclad billets. The seven clad billets were extruded with preheat temperatures ranging from 2400° to 3800° F. When billet transfer time (4 to 8 sec) was taken into consideration, the adjusted extrusion temperatures of these billets were 2370° to 3640° F. Throughout the remainder of this report, the term extrusion temperature will be used to designate adjusted extrusion temperature. Four of the seven unclad billets were successfully extruded at extrusion temperatures of 2750° to 3880° F. The three remaining billets (12, 13, and 14) which were preheated to 2600° F, stalled the press and did not extrude.

An unclad billet (11) was extruded at 2750° F and a velocity of 0.4 inch per second, whereas a clad billet (7) was extruded at 2370° F and a velocity of 4.4 inches per second. The fact that a clad billet extruded at a lower temperature than an unclad one had a higher extrusion velocity indicates that even lower temperatures than used in this study could well be adequate for the extrusion of clad tungsten billets. It also suggests that difficult-to-extrude materials, such as tungsten alloys or composites, may be incorporated into relatively thick cans and thus be successfully extruded at temperatures at which the unclad material might otherwise stall the press.

Tensile Properties

Results of room-temperature and elevated-temperature tensile tests carried out on specimens of the clad and unclad extrusions are presented in table III; these data include tensile strength, percent reduction in area at fracture, hardness, grain size, type of microstructure, and an estimate of failure mechanisms based on visual observations of the fracture.

Room-temperature tensile strengths are plotted in figure 3 as functions of adjusted extrusion temperature. At room temperature both the clad and unclad materials showed increasing tensile strengths as the extrusion temperature was decreased. For a given extrusion temperature, unclad extrusions yielded higher room-temperature tensile strengths than the clad ones. However, no reason for this difference in observed strength can be offered at this time. With cladding, the highest strength (approximately 113 000 psi) was obtained at an extrusion temperature of 2420° F. Without cladding, the highest strength (approximately 117 000 psi) occurred with an extrusion temperature

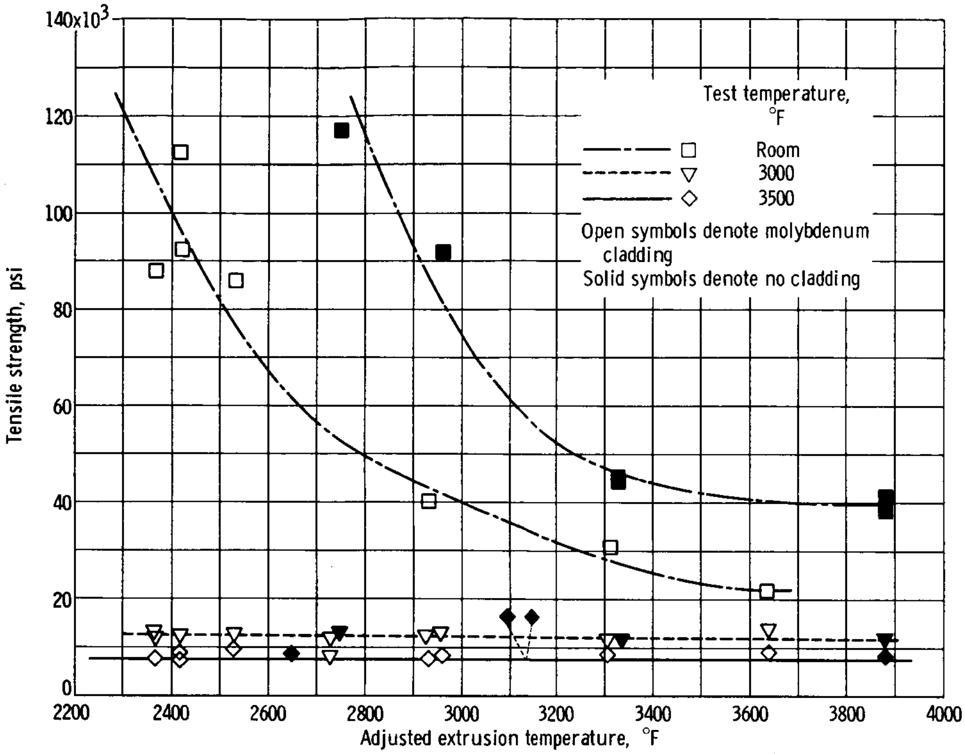


Figure 3. - Tensile strength of tungsten as function of extrusion temperature.

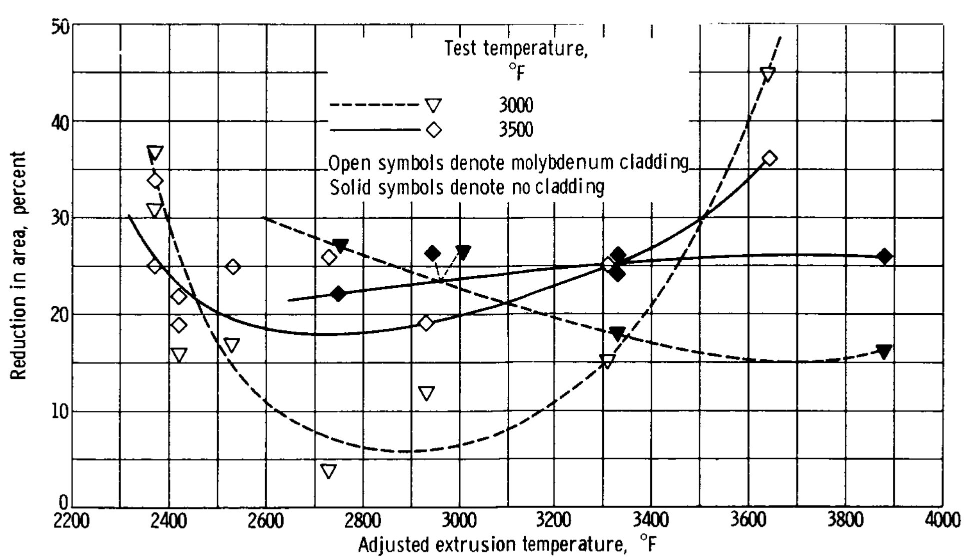


Figure 4. - Reduction in area of tensile test specimens as function of extrusion temperature.

of 2750° F. The minimum strength observed with any room-temperature test was of the order of 22 000 pounds per square inch and was obtained for a clad extrusion specimen.

Tensile tests conducted at 3000° and 3500° F indicated that the elevated-temperature tensile strength was independent of extrusion temperature and extrusion technique (i.e., clad or unclad). Also, the strength level achieved at 3000° F was only slightly above that for the 3500° F tests. The fact that the elevated-temperature tensile strengths were not adversely affected by extrusion (with or without cladding) at the lower temperature indicated that the extrusion process in itself had not damaged the material. Had damage occurred at lower extrusion temperatures, elevated-temperature exposure prior to elevated-temperature tensile testing could have caused stress relief and thus made apparent any microdamage obscured by the cold work retained in room-temperature tests.

Figure 4 is a plot of the reduction in area at fracture of tensile specimens as a function of extrusion temperature. Since all specimens tested at room temperature failed without any measurable reduction in area, only the 3000° and 3500° F data are shown. The actual values (with one exception) fell within the range 12 to 44 percent. Extrusion temperature appears to exert a significant influence on the reduction in area of tensile test specimens made from the clad extrusions. As shown in figure 4, the ductility curves for both 3000° and 3500° F tests of clad extruded materials are U-shaped; that is, greater reductions were obtained at the highest and lowest extrusion temperatures than in the intermediate range. In contrast, with specimens from the unclad extrusions there appeared to be a lesser effect of extrusion temperature on the reduction-in-area values. However, at 3500° F the curve shows a slight upward trend, while at 3000° F a slight downward trend is indicated. No apparent reason could be found for the observed differences in ductility response between the clad and unclad materials.

Hardness

Hardness values obtained on the as-extruded materials and on failed specimens subsequent to tensile testing are shown in figure 5. As would be expected, there was no difference between the as-extruded hardness and the hardness after room-temperature testing; the curves for both the clad and unclad materials are essentially the same and are flat between approximately 3900° and 2800° F. For extrusion at temperatures below 2800° F, the hardness of the clad extruded billets increased as extrusion temperature decreased. Although a considerable amount of scatter exists, the hardness after 3000° and 3500° F testing for both clad and unclad materials exhibited a steady decrease between approximately 3900° and 2800° F followed by an upward trend for clad materials

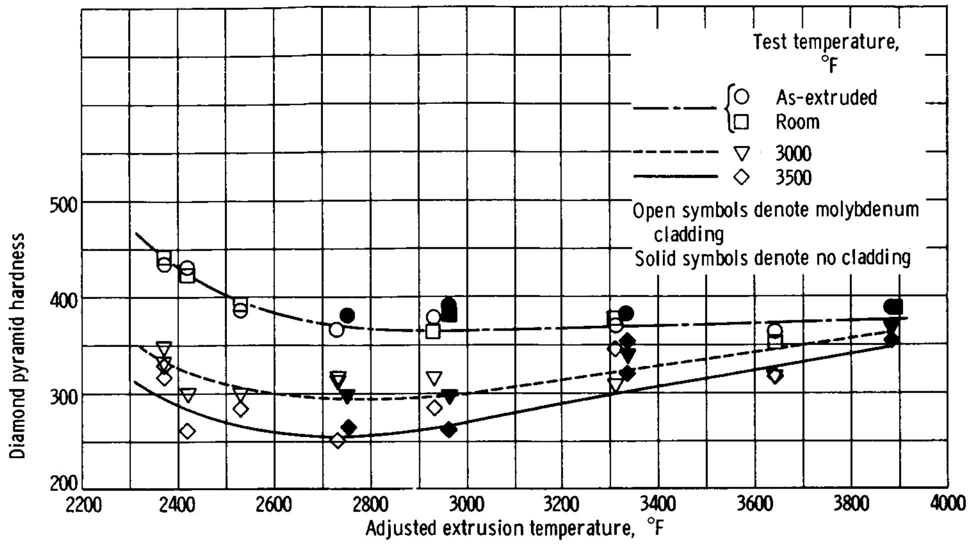


Figure 5. - Hardness after tensile testing as function of extrusion temperature.

extruded at temperatures below 2800° F. (The lowest temperature for successful extrusion with the unclad materials was 2750° F.) Again, the curves for the clad and unclad billets were essentially similar. As expected, the hardnesses obtained after testing at room temperature were highest, those tested at 3000° F were second, and those tested at 3500° F were third.

Grain Size

Grain-size measurements of specimens in the as-extruded condition and after tensile testing at room temperature and at 3000° and 3500° F are shown in figure 6. On an overall basis, the gross grain-size differences observed in the specimens were considerable (ASTM no. 5.5 to 13). As expected, however, materials extruded at higher temperatures generally had the largest grain size (smallest ASTM grain-size number). It is also apparent that post-test grain size tended to increase with increasing test temperature.

Reduction Ratio

All billets utilized in this study were extruded at a nominal reduction ratio of 12:1. The calculated reduction ratios based on container size (provided the billets upset to fill the container completely prior to extrusion) were essentially 12:1 in all cases. Based on the initial and final measured diameters, however, the reduction ratios ranged from

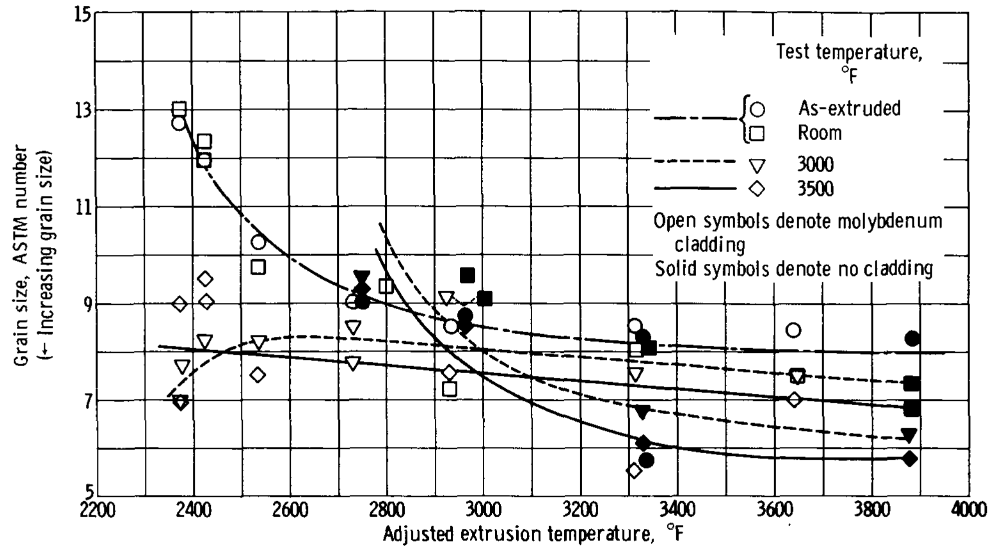


Figure 6. - Grain size after tensile testing as function of extrusion temperature.

10.1:1 to 10.9:1 for the clad materials and from 10.4:1 to 10.9:1 for the unclad materials. In all cases (clad and unclad) there was no temperature-dependent trend of reduction ratio. The absence of such a trend in the reduction of the tungsten in the molybdenum-clad billets suggests that the relative deformation resistance of the two materials was essentially constant over the range of extrusion temperatures utilized.

Advantages of Clad Extrusion

A possible advantage resulting from the use of molybdenum cladding is a lubrication effect due to the formation of volatile molybdenum oxide at extrusion temperatures. The lubrication effect tends to be substantiated by the greater ease of extrusion with clad billets as compared to unclad billets. For the same extrusion pressure the clad billets not only extruded at a greater speed, but also produced only a negligible die wash, whereas those without cladding produced as much as 0.040 inch die wash.

Although molybdenum cladding may contribute a lubrication effect, the use of a thin cladding did not provide the extrusion advantage of thick cans (ref. 7 and unpublished data obtained at the Lewis Research Center), as noted in the present study. The specific advantage of the thick cladding used in this study appears to be a greater yield of useful material. Since the molybdenum is more plastic than the tungsten at elevated temperatures, the thick cans may result in a relatively greater unit stress being applied to the tungsten core compared to that applied to the tungsten in an unclad billet of the same total diameter. Further, it is possible that the more deformable molybdenum exerts a quasi-hydrostatic force on the tungsten core, which enhances its deformability.

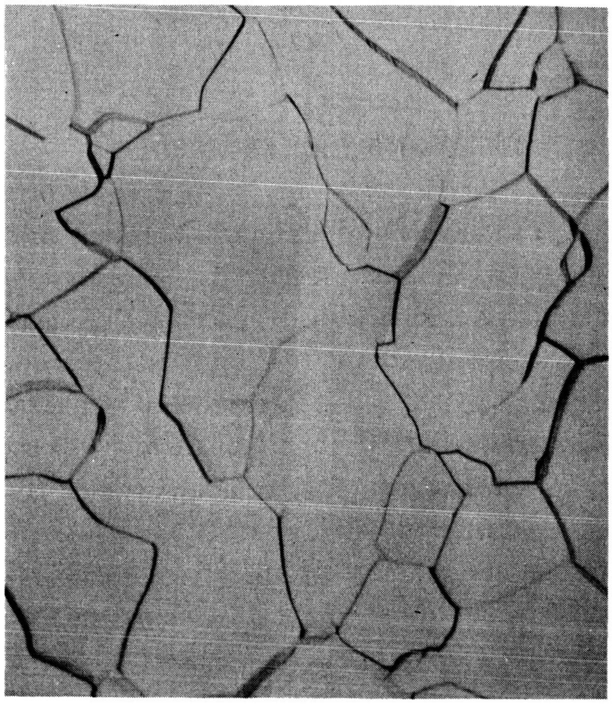
Metallographic Examination

A general classification of the types of structure obtained in the as-extruded and the as-tested specimens is presented in tables II and III, respectively. The microstructures obtained as functions of extrusion temperatures are shown in figure 7(a) for the clad billets and figure 7(b) for the unclad billets. All microstructures exhibited equiaxed grains; however, in the case of billets 6 and 7 (extrusion temperatures of 2420° and 2370° F, respectively) the structures were only partially recrystallized.

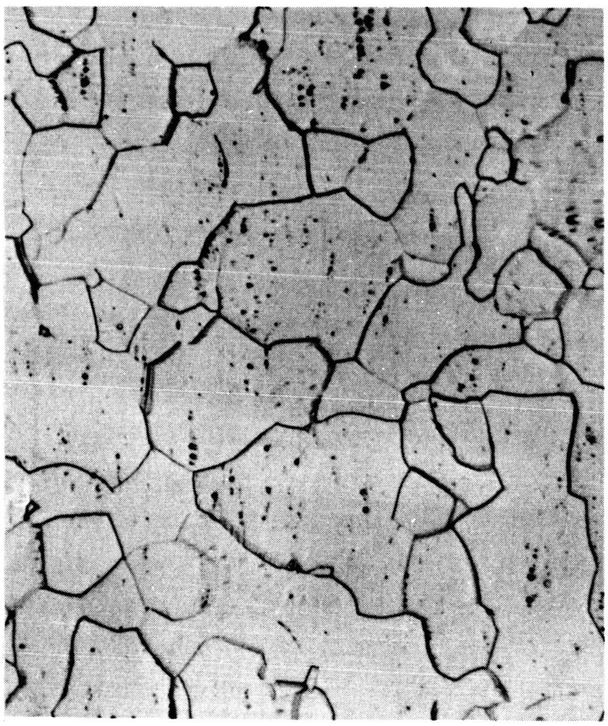
Typical microstructures after tensile testing are shown in figure 8. The microstructures of the specimens tensile tested at room temperature indicated brittleness in all instances regardless of extrusion temperature or technique. The fracture path proceeded both intergranularly and along cleavage planes. After high-temperature tensile testing, the microstructures also appeared independent of extrusion temperature or technique; however, the fracture path was predominantly, if not entirely, intergranular. Extensive grain-boundary void formation was evident (fig. 8). The grains appear equiaxed, which indicates that either they elongated during testing but recrystallized to become equiaxed, or they remained undeformed and grain boundary sliding occurred during tensile testing at elevated temperature. The fact that substantial reductions in areas occurred suggests that the grains actually elongated but then recrystallized to become equiaxed.

General Comments on Test Results

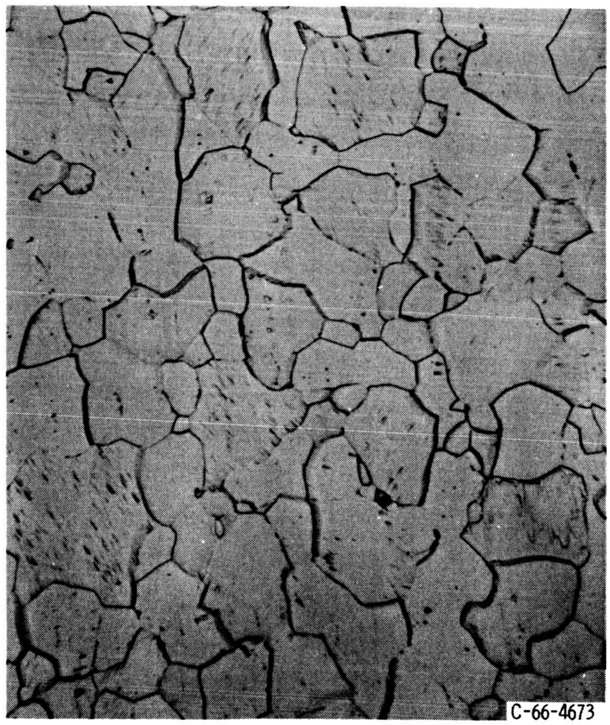
Although there was a considerable spread in the measured properties of the materials studied, there appeared to be no consistent correlation between tensile strength, extrusion temperature, clad as opposed to unclad technique, reduction in area, hardness, or grain size. The lack of pronounced correlation between elevated-temperature tensile strength and grain size was somewhat surprising in view of the usual concept which holds that the finer the grain size, the higher the anticipated tensile strength. The results of this study also seem to indicate that room-temperature tensile strength is a more sensitive indicator of differences in the amount of retained energy than is either hardness or grain size.



Billet 1, extruded at 3640° F



Billet 2, extruded at 3310° F

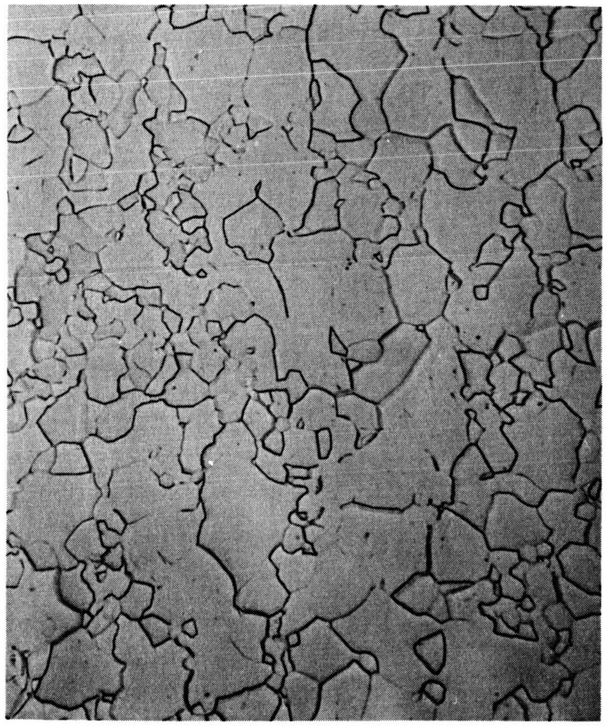


Billet 3, extruded at 2930° F

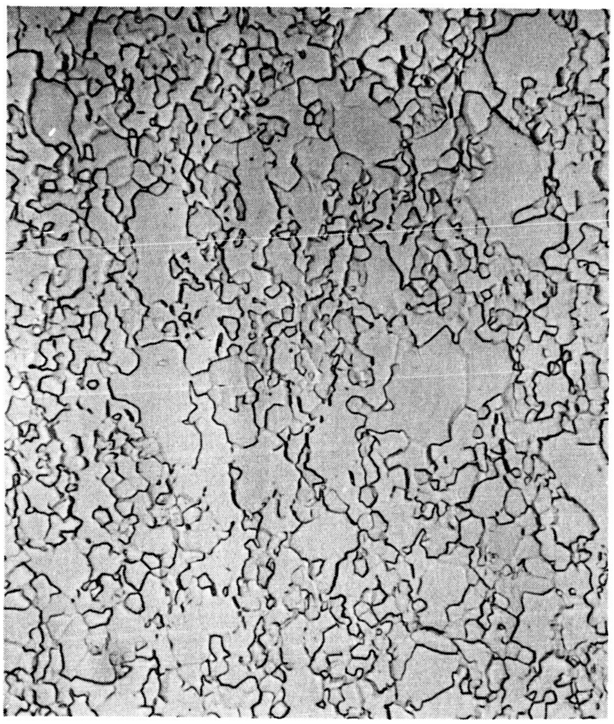
(a) Molybdenum-clad billets.

Figure 7. - Effect of adjusted extrusion temperature on microstructure of as-extruded billets. Longitudinal sections; nominal extrusion ratio, 12:1; etchant, Murakami's reagent. x500.

Billet 4, extruded at 2730° F



Billet 5, extruded at 2530° F

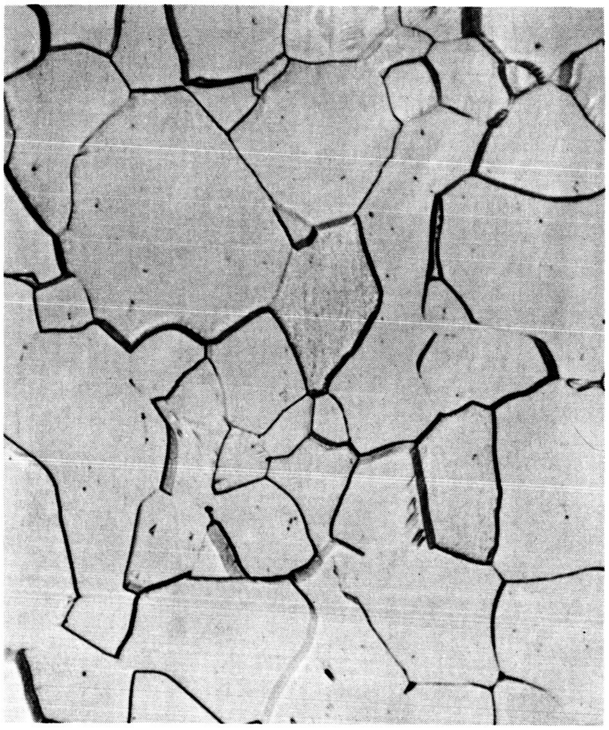


Billet 6, extruded at 2420° F

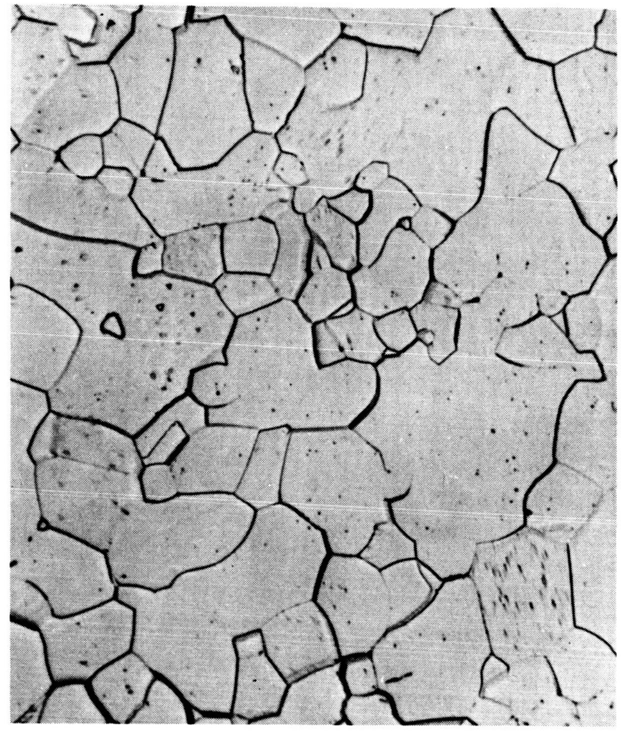
Billet 7, extruded at 2370° F

(a) Concluded.

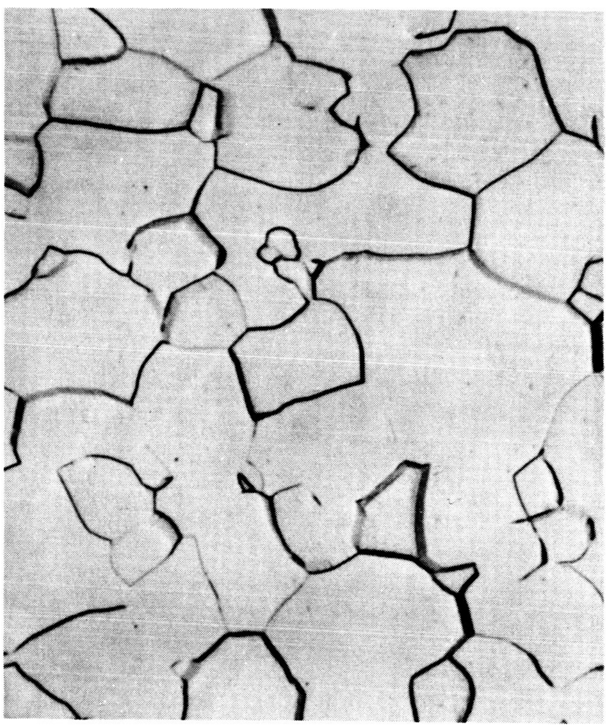
Figure 7. - Continued.



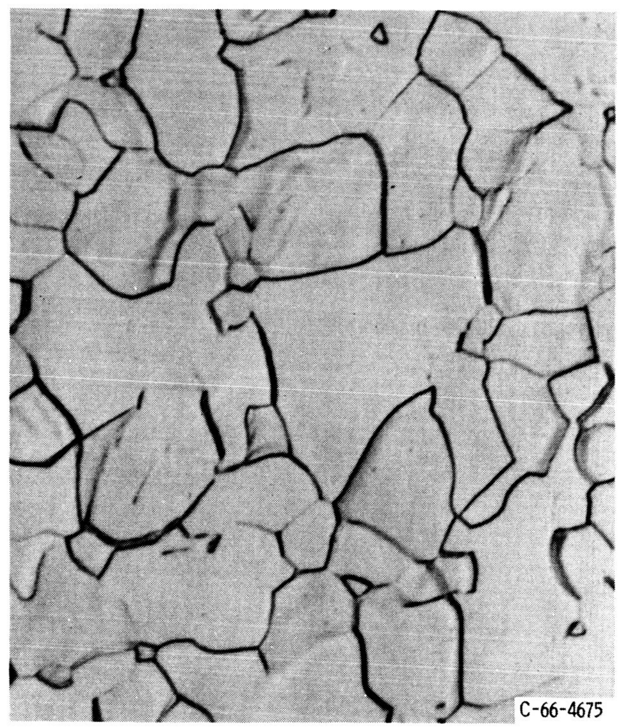
Billet 8, extruded at 3880° F



Billet 9, extruded at 3330° F



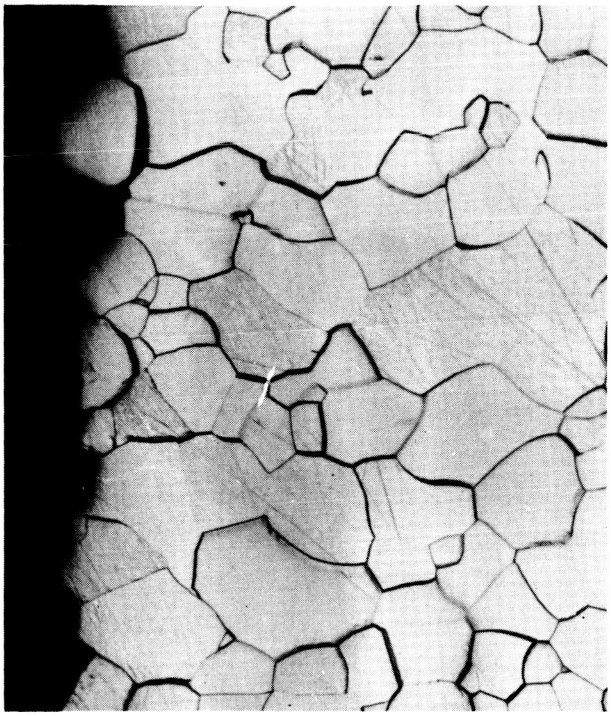
Billet 10, extruded at 2960° F



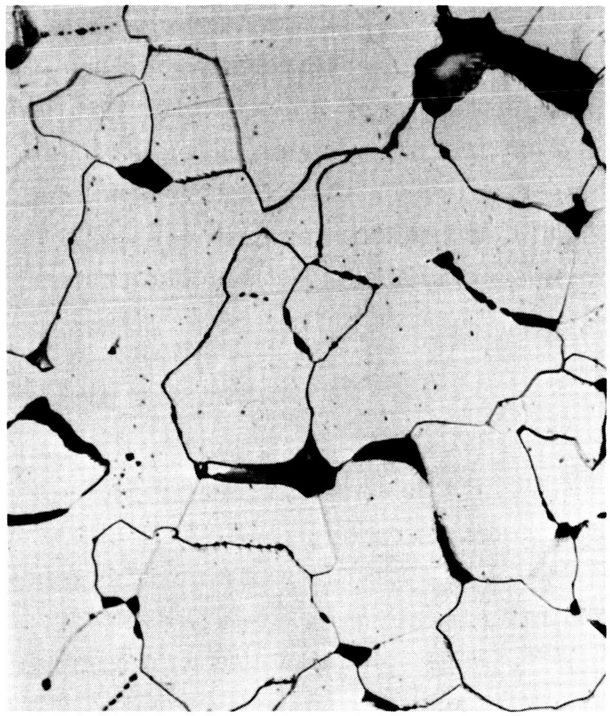
Billet 11, extruded at 2750° F

(b) Unclad billets.

Figure 7. - Concluded.



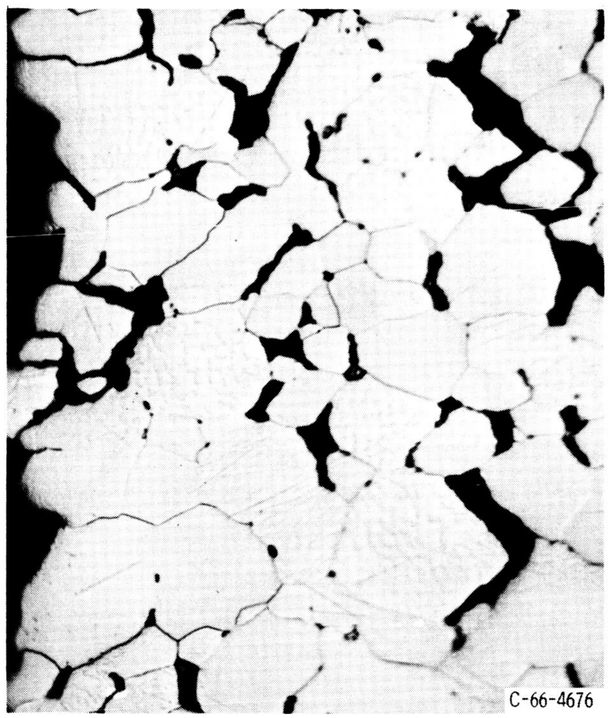
Billet 1, extruded at 3640° F and tensile tested at room temperature (x250)



Billet 1, extruded at 3640° F and tensile tested at 3500° F (x500)

(a) Molybdenum-clad billet.

Billet 9, extruded at 3330° F and tensile tested at room temperature (x100)



Billet 10, extruded at 2960° F and tensile tested at 3500° F (x500)

(b) Unclad billets.

Figure 8. - Typical microstructures of fracture areas of extruded tungsten after tensile tests. Etchant, Murakami's reagent.

CONCLUDING REMARKS

The results of this study have shown the possibility of extruding clad tungsten at considerably lower temperatures than unclad tungsten. Such needs for lower temperature extrusion may arise during extrusion of high-strength alloys or composite materials. Dispersion-strengthened materials, in general, should contain stored energy. Lowest possible extrusion temperatures would promote retention of stored energy and could be of benefit under some circumstances.

SUMMARY OF RESULTS

An investigation carried out to determine the influence of cladding on the properties of tungsten extruded over a range of preheat temperatures from 2400° to 4000° F (actual extrusion temperatures of approximately 2370° to 3880° F) and at a nominal 12:1 reduction ratio led to the following results:

1. Tungsten billets clad with nominally 1/4-inch-thick powder-metallurgy molybdenum were successfully extruded with preheat temperatures as low as 2400° F (actual extrusion temperature of approximately 2370° F). Tungsten without cladding could not be extruded at preheat temperatures below 2800° F (actual extrusion temperature of approximately 2750° F).

2. The reduction ratios based on initial and final diameters of the tungsten extrusions were similar for both the clad and unclad materials. The reduction ratios for the clad billets varied from 10.1:1 to 10.9:1 and for the unclad billets from 10.4:1 to 10.9:1. There was no trend in the reduction ratio of the billets as a function of extrusion temperature.

3. The room-temperature tensile strengths of specimens from the unclad extrusions were greater than those of the clad extrusions for equivalent extrusion temperatures. Both materials exhibited an increase in strength with decreasing extrusion temperature.

4. At both 3000° and 3500° F the strength levels obtained were independent of extrusion technique and temperature.

5. All materials tested at room temperature failed without measurable reduction in area. For the 3000° and 3500° F tests, specimens from the clad billets extruded at the upper and lower temperature extremes were more ductile than those extruded at intermediate temperatures (2730° to 3310° F). The unclad billets exhibited relatively little

change in ductility as a function of extrusion temperature.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 20, 1966,
129-03-01-05-22.

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